The constructive role of decisions: implications from a quantum approach

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14. ABSTRACT
The last interim report was submitted Jan. 2015. This grant had two objectives. The first was to explore the nature of constructive influences in decision making. The second concerned understanding decision making in Prisoner's Dilemma. **First objective; constructive judgments. This is the idea that sometimes making a decision can alter the underlying relevant mental state. Simply put, if a person is uncertain whether e.g. a radar signal represents a threat or not, then being asked to decide (Does this signal represent a threat?) changes the underlying mental representations. If the person decides that the radar does represent a threat, he/she would perceive it as more threatening, than previously. This is an important idea since it impacts on our understanding of how questions, ratings, other cognitive measurements can actually alter the mental states. Part of the motivation for studying this question is our expertise with quantum theory, an innovative mathematical framework for understanding cognition, which has to predict that the resolution of any e.g. question alters the mental state in a specific way. Up to the point of the first report, we had validated the main idea (as outlined in the grant proposal), with two main publications (appr. six distinct experiments; note, several other outcomes had been produced within this grant). Between the last report and the end of the grant we pursued a mathematically more sophisticated and empirically more ambitious demonstration, which related to the impact of increasing the density of intermediate judgments on an eventual determination. We found, as our model predicted, that a higher density of intermediate judgments slowed down opinion change. We think this finding is important for AFOSR. For example, consider the issue of trust in an autonomous agent: suppose an operator monitors the performance of the agent.

15. SUBJECT TERMS
EOARD, Quantum Probability, Human Modeling, Human Decision Making

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Constructive influences

Human decisions often involve uncertain events; so, to understand decision making, we must understand the cognitive principles for probabilistic inference. We call Quantum Theory (QT) the rules for how to assign probabilities to events from quantum mechanics, without any of the physics. Classical Theory (CT) has been the dominant probabilistic framework in decision theory, achieving excellent empirical coverage (Oaksford & Chater, 2009; Tenenbaum et al., 2011) and supported by powerful prior arguments (e.g., the Dutch Book theorem; de Finetti et al., 1993). So why consider theories other than CT in cognition? Because there have been some key empirical findings, mostly from the influential Tversky (one of the most cited psychologists of all time), Kahneman (Nobel prize in economics) tradition, persistently problematic for CT. Some researchers have taken such results as evidence that decision theory should not be based on (any) formal probabilistic framework. We have been at the forefront of an alternative approach, exploring the potential of QT in decision theory (Busemeyer & Bruza, 2011; Pothos & Busemeyer, 2013).

QT and CT are founded on different axioms and their predictions often diverge; what is intuitive in QT theory is often incorrect in CT and vice versa. The transformative potential of QT in decision theory lies in that QT involves several unique concepts, such as interference, entanglement, superposition, and, the focus of the present proposal, collapse. The QT collapse postulate is that making a measurement of a system forces the 'system' to identify with the result of the measurement. In physics, measuring the position of an elementary particle makes the particle have a particular position, the one indicated by the measurement; strangely, the mathematics of QT (often) require that prior to the measurement the particle cannot be said to have any position. In decision making, the analogous implication is that certain judgments force a change of the cognitive state, such that it identifies with the judgment outcome. The collapse postulate is a unique idea in decision theory, even though broadly analogous ideas have already been considered (relating to constructive influences in cognition, see below). **Can we use the collapse postulate in decision theory to make novel, interesting predictions?**

Experimental and mathematical work, part 1

Consider pairs of images, always of opposite valence (polarity); valence can be affect, in which case images would have either positive affect (P) or negative affect (N), but can also be e.g. trustworthiness or disposition towards a political candidate (for consistency, we use the labels P, N to denote high or low valence levels, regardless of whether valence is affect or something else). In each pair, the second image is always rated, but the first image is only sometimes rated (Figure 1). Compare the rating for the second image, depending on whether the first image was rated or not. Across six experiments in two papers (White et al., 2014, 2015), we supported a key interaction, which we call the **evaluation bias** (EB): with the intermediate rating, the rating for the second image is more intense, than without (Figure 2).
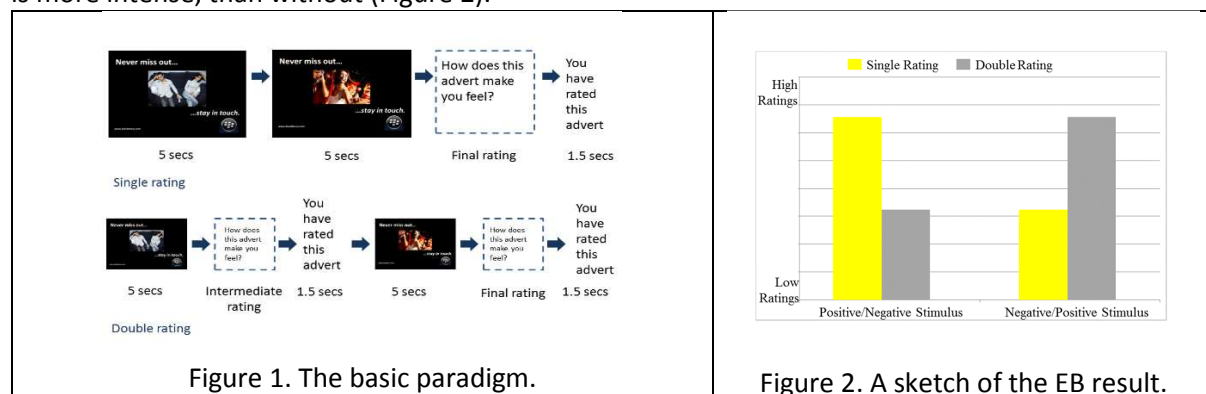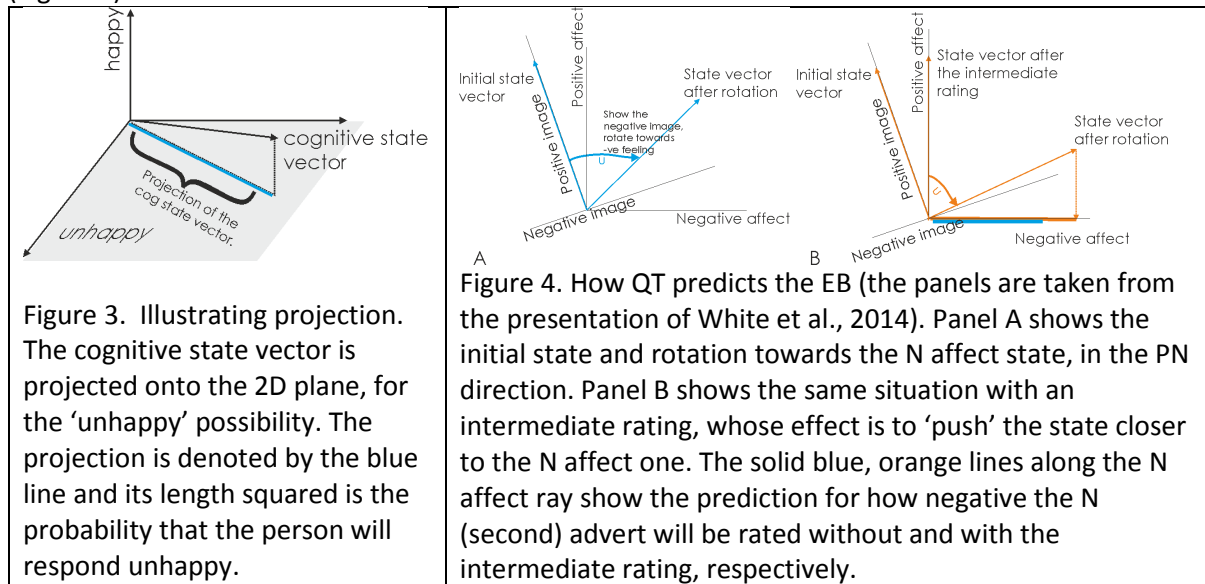

Figure 1. The basic paradigm.

Figure 2. A sketch of the EB result.

Using QT, the EB has a straightforward account. In QT, the state of the relevant system is represented as a vector in a multidimensional space. In decision theory, the state corresponds to the mental state of a decision maker, prior to a decision. In that space, different subspaces correspond

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to different questions. For example, in Figure 3, we show an example of a 3D space, representing two questions: happy (represented with a 1D subspace) and unhappy (2D subspace; note, there does not have to be symmetry in dimensionalities). If a person is asked whether she is happy/unhappy, then the probability she will produce different answers depends on the projection of the state vector to each subspace. In this example, because the state vector is closer to the unhappy subspace, there is a greater probability she will respond 'unhappy'. If she does respond unhappy, then the state vector changes to become a (normalized) vector along the projection. This is the collapse postulate: making a judgment changes (in a specific way) the state vector. Regarding the EB, we constructed a simple representation involving P, N affects and P, N pictures (White et al., 2014). Without an intermediate judgment, in the e.g. PN direction, showing the N image leads to a rotation of the state vector towards the N subspace. With the intermediate judgment, first the state vector collapses onto the P affect ray and then undergoes the *same* (cf. Laming, 1984; Stewart et al., 2005) rotation towards the N subspace, which means that the eventual projection is longer, i.e., the intermediate rating leads to a more negative valuation of the second, N stimulus; analogously, in the NP order, the intermediate rating leads to a more positive evaluation of the second, P stimulus (Figure 4).

Figure 3. Illustrating projection. The cognitive state vector is projected onto the 2D plane, for the 'unhappy' possibility. The projection is denoted by the blue line and its length squared is the probability that the person will respond unhappy.

Figure 4. How QT predicts the EB (the panels are taken from the presentation of White et al., 2014). Panel A shows the initial state and rotation towards the N affect state, in the PN direction. Panel B shows the same situation with an intermediate rating, whose effect is to 'push' the state closer to the N affect one. The solid blue, orange lines along the N affect ray show the prediction for how negative the N (second) advert will be rated without and with the intermediate rating, respectively.

Experimental and mathematical work part 2

The original experimental paradigm for the EB included a number of simplifications. Consider a more realistic decision making situation, whereby participants have to make an eventual determination, based on a series of evidence. In addition, intermediate determinations can be made (which can be thought of as updates or preliminary determinations, anticipating the final one). Can these intermediate determinations affect the final one? Specifically, participants read a story about a hypothetical murder suspect, Smith. Smith was initially considered innocent by most participants. Then, at each time step, participants were presented with an (approximately) identically strong piece of evidence suggesting that Smith was in fact guilty. The task was designed as a generic situation of opinion change, from presented information.

We developed a state of the art cognitive model, based on QT, on how opinion change would be affected by intermediate judgments. If $T/N, 2T/N \ldots T$ are the times when the judgments are being made, then,

$$Prob^Q('survival', N) = Prob\left(I\ at\ \frac{T}{N}\ AND\ I\ at\ \frac{2T}{N}\ AND\ \ldots I\ at\ T\right) =$$

$$(1-\epsilon)^{N+1}\prod_{i=0}^{N-1}\cos^2\left(B\left(\frac{iT}{N}, \frac{(i+1)T}{N}\right)\right)$$

$$+\epsilon(1-\epsilon)^N \sin^2\left(B\left(\frac{(N-1)T}{N},T\right)\right)\prod_{i=0}^{N-2}\cos^2\left(B\left(\frac{iT}{N},\frac{(i+1)T}{N}\right)\right)+O(\epsilon^2)$$

(where survival probability is the probability that the initial opinion does not change and

$$B(t_m,t_n)=\alpha\sum_{i=m+1}^{n}a_i\ e^{-\beta(i-m-1)^2}$$

is a function concerning the impact of evidence at t_m, relative to evidence present at t_n)

All model parameters were fitted at a first calibration step. Then, without further parameter fitting, the model was asked to predict the impact of intermediate judgments on opinion change. Indicative results are shown in Figure 5.
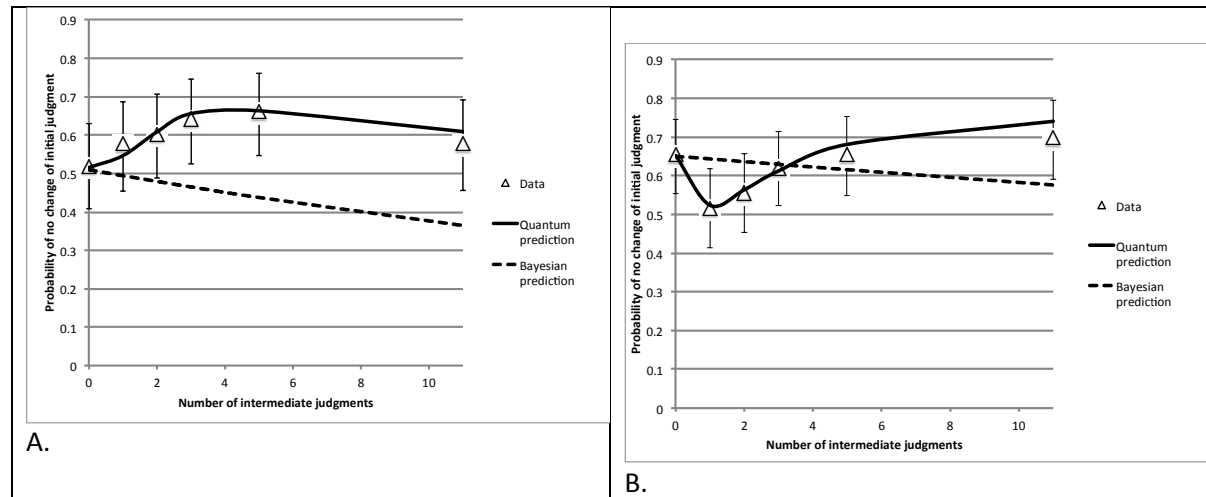

Figure 5. Evaluating the models: Survival probability for *N* intermediate judgments, for the QT, Bayesisn models, against empirical results (A: Experiment 1, N=75, 71, 73, 70, 71, 64, for each data point; B: Experiment 2, N=90, 89, 88, 95, 81, 73.). Data points are participant averages and error bars show 95% HDI of the posterior.

St. Petersburg paradox

Consider a 'doubling game', in which a player starts with 1 unit. On each trial, the player can choose to either stop playing and take home her winnings or double her accumulated units. However, if she doubles on trial *Y*, she loses all and the game ends. The number of *Y* has been vaguely specified, e.g., a person filled a sheet with random digits, permuted them, and so produced *Y* (since it is impossible to write an infinite number of digits on a sheet of paper, the number *Y* is finite). To justify stopping on trial *N*, the player must think that Prob(*N*=*Y*) is at least ½. But this is always unreasonable. The player can attempt to guess the probability distribution for *Y* (i.e. a Bayesian prior). However, having successfully reached trial *N*-1 without losing, she will surely form a posterior distribution that predicts considerable probability for numbers above *N*. Why? Because, seeing *N*-1 ensures that the number of digits written down were sufficiently numerous to generate *N*-1. Knowing this makes it likely that numbers higher than *N*-1 will be produced. Thus, the paradox in the doubling game is caused by the vague specification of *Y* (e.g., Bonini et al., 1999). Note that a prior could be chosen that will delay the stopping decision to such a large trial number (e.g. 100**(100**100)) that ruin would certainly occur, but this prior is not helpful. Whichever way one attempts to specify a prior on *Y*, we suggest that this will not resolve the paradox.

Using QT, we developed a model for stopping behavior in such a doubling game and developed a corresponding empirical prediction. As the project progressed, we devoted more effort regarding the part on constructive judgments. This was because direction provided more promising further avenues and because of our perception that it had greater applied value.

Other work: digital context in moral decision making

In this digital age, we spend a lot of time interacting with computer screens, smartphones and other digital gadgets. A key distinction regarding moral judgments concerns deontological versus utilitarian decisions (Singer, 1991; Chaiken & Trope, 1999). Recent dual-process accounts of moral judgment contrast deontological judgments, which are generally driven by automatic/unreflective/intuitive responses, prompted by the emotional content of a given dilemma, with utilitarian responses, which are the result of unemotional/rational/controlled reflection, driven by conscious evaluation of the potential outcomes (Greene et al., 2001; Greene & Haidt, 2002; Greene et al., 2004; Koenigs et al., 2007). In this account, an individual's ethical mind-set (rule-based vs. outcome-based, Barque-Duran et al., 2015; Cornelissen et al. 2013) can play a central role. A deontological perspective evaluates an act based on its conformity to a moral norm (Kant, 1785/1959) or perhaps just a rule (such a law). By contrast a consequentialist/utilitarian perspective evaluates an act depending on its consequences (Mill, 1861/1998). We explored whether a Digital Context (i.e. using a digital device such a Smartphone or a PC, as hundreds of millions of individuals do every day) can have a systematic impact on these processes. To do so, we employed the well-known trolley dilemma, where one imagines standing on a footbridge overlooking a train track. A small incoming train is about to kill five people and the only way to stop it is to push a heavy man off the footbridge in front of the train. This will kill him, but save the five people. A utilitarian analysis dictates sacrificing one to save five; but this would violate the moral prohibition against killing. Imagining physically pushing the man is emotionally difficult and therefore people typically avoid this choice (Thomson, 1985). Figure 6 illustrates the paradigm (so-called 'Fat Man' variation). Our results indicated that, under most circumstances, using a smartphone led to more utilitarian judgments.
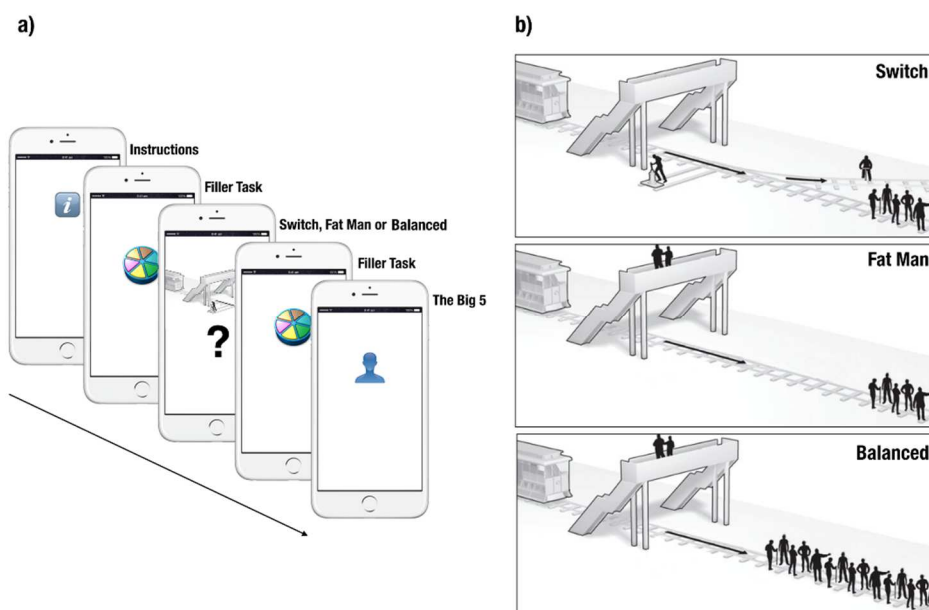

Fig. 1. A) The experimental paradigm used in the Smartphone condition in Experiment 1. B) The illustrations used in each of the three moral conditions (Switch, Fat Man and Balanced).

Other work: human causal reasoning

Our work on this grant, applying QT on human decision making, enabled collaborations on related projects on human causal reasoning. The predominant approach on human causal reasoning is Bayes Nets. However, we have been pursuing a model based on QT, which is motivated by results showing a divergence between Bayes Nets principles and human behaviour.

-Conference papers presented (include title, authors & conference/location)
1. Yearsley, J. M., Trueblood, J. S., & Pothos, E. M. (in press). When are representations of causal events quantum versus classical? In Proceedings of the 38th Annual Meeting of the Cognitive Science Society.
2. Yearsley, J. M. & Pothos, E. M. (in press). Intermediate judgments inhibit belief updating: Zeno's paradox in decision making. In Proceedings of the 38th Annual Meeting of the Cognitive Science Society.
3. Trueblood, J. S., Mistry, P. K., & Pothos, E. M. (2015). A Quantum Bayes Net approach to causal reasoning. In E. Dzhafarov, R. Zhang, S. Joardan, & V. Cervantes (Eds.) *Contextuality: from quantum physics to psychology*, pp.429-444. World Scientific.
(Output from Purdue University workshop in contextuality, Autumn 2014.)
4. Barque-Duran, A., Pothos, E. M., Yearsley, J. M., Hampton, J. A., Busemeyer, J. R., & Trueblood, J. S. (2015). Similarity judgments: from classical to complex vector psychological spaces. In E. Dzhafarov, R. Zhang, S. Joardan, & V. Cervantes (Eds.) *Contextuality: from quantum physics to psychology*, pp. 395-428. World Scientific.
(Output from Purdue University workshop in contextuality, Autumn 2014.)
5. Mistry, P. K., Trueblood, J. S., Vandekerckhove, J., & Pothos, E. M. (2015). A latent-mixture quantum probability model of causal reasoning within a Bayesian inference framework. In *Proceedings of the 37ᵗʰ Annual Conference of the Cognitive Science Society (Pasadena USA).*
6. Yearsley, J. M., Pothos, E. M., Barque-Duran, A., & Hampton, J. A. (2015). Diagnosticity: some theoretical and empirical progress. In *Proceedings of the 37ᵗʰ Annual Conference of the Cognitive Science Society (Pasadena USA).*
7. Yearsley, J. M. & Pothos, E. M. (2015). Towards an empirical test of realism in cognition. In *Proceedings of the 37ᵗʰ Annual Conference of the Cognitive Science Society (Pasadena USA)*.
8. Barque-Duran, A., Pothos, E. M., Yearsley, J. M., & Hampton, J. A. (2015). Patterns and evolution of moral behavior: moral dynamics in everyday life. In *Proceedings of the 37ᵗʰ Annual Conference of the Cognitive Science Society (Pasadena USA)*.
9. Yearsley, J. M., Pothos, E. M., Hampton, J. A., & Barque Duran, A. (2014). Towards a quantum probability theory of similarity judgments. In *Proceedings of the Quantum Interaction Conference (Filzback Switzeland)*.
10. Yearsley, J. M. & Pothos, E. M. (2014). Towards an empirical test of realism in cognition. In *Proceedings of the Quantum Interaction Conference (Filzback Switzeland)*.
11. Trueblood, J. S. & Pothos, E. M. (2014). A quantum probability approach to human causal reasoning. In *Proceedings of the 36ᵗʰ Annual Conference of the Cognitive Science Society (Quebec Canada)*. Austin TX: Cognitive Science Society.

-Archival papers submitted & status (Title, journal, authors & publish date)
1. Basieva, I., Pothos, E. M., Trueblood, J. Khrennikov, A., & Busemeyer, J. R. (in press). Quantum probability updating from zero priors (by-passing Cromwell's rule). ***Journal of Mathematical Psychology***.
2. Yearsley, J. M. & Pothos, E. M. (2016). Zeno's paradox in decision making. ***Proceedings of the Royal Society B***, 283, 20160291.
3. Barque-Duran, A., Pothos, E.M., Yearsley, J.M., & Hampton, J.A. (in press). Patterns and evolution of moral behavior: moral dynamics in everyday life. ***Thinking & Reasoning***.
4. Conway, M.A., Pothos, E.M., & Turk, D.J. (in press). The self-relevance system? ***Cognitive Neuroscience***.

5. Pothos, E. M., Barque-Duran, A., Yearsley, J. M., Trueblood, J. S., Busemeyer, J. R., & Hampton, J. A. (in press). Progress and current challenges with the Quantum Similarity Model. *Frontiers in Psychology*.
6. White, L.C., Barque-Duran, A., & Pothos, E.M. (in press). An investigation of a quantum probability model for the constructive effect of affective evaluation. *Philosophical Transactions of the Royal Society A*.
7. Busemeyer, J.R., Wang, J., Pothos, E.M., & Trueblood, J.S. (2015). The conjunction fallacy, confirmation, and quantum theory: comment on Tentori, Crupi, & Russo (2013). *Journal of Experimental Psychology: General*, 144, 236-243.
8. Pothos, E. M. & Trueblood, J. S. (2015). Structured representations in a quantum probability model of similarity. *Journal of Mathematical Psychology*, 64, 35-43.
9. White, L.C., Pothos, E.M., & Busemeyer, J R. (2015). Insights from quantum cognitive models for organizational decision making. *Journal of Applied Research in Memory and Cognition*, 4, 229-238.
10. Pothos, E.M. & Reppa, I. (2014). The fickle nature of similarity change as a result of categorization. *The Quarterly Journal of Experimental Psychology*, 67, 2425-2438.
11. Pothos, E.M. & Busemeyer, J.R. (2014). In search for a standard of rationality. *Frontiers in Cognitive Science*, 5, 1-3.
12. Pothos, E.M., Shiffrin, R.M., & Busemeyer, J.R. (2014). The dynamics of decision making when probabilities are vaguely specified. *Journal of Mathematical Psychology*, 59, 6-17.
13. Trueblood, J. S., Pothos, E. M., & Busemeyer, J. R. (2014). Quantum probability theory as a common framework for reasoning and similarity. *Frontiers in Cognitive Science*, 5.
14. White, L.C., Pothos, E.M., & Busemeyer, J.R. (2014). Sometimes it does hurt to ask: the constructive role of articulating impressions. *Cognition*, 133, 48-64.
15. Yearsley, J.M. & Pothos, E.M. (2014). Challenging the classical notion of time in cognition: a quantum perspective. *Proceedings of the Royal Society B*, 281, 1471-1479.
16. Ziori, E., Pothos, E.M., & Dienes, Z. (2014). Role of prior knowledge in implicit and explicit learning of artificial grammars. *Consciousness & Cognition*, 28, 1-16.
17. Pothos, E. M., Busemeyer, J. R., & Trueblood, J. S. (2013). A quantum geometric model of similarity. *Psychological Review*, 120, 679-696.

-Collaborations with government and defense, both US and any other nation

I have been in contact with Mike Miller (AFIT) over the possiiblity of pursuing an application of my work towards a paradigm of direct relevance to the USAF.

-Other funding not related to the project, but complementary in nature

2013: E. M. Pothos, J. R. Busemeyer, J. Trueblood, & J. A. Hampton: 24 month Leverhulme Trust grant to study "Quantum similarity: harnessing the flexibility of human similarity judgment." Value: **£98,962**.

This grant has now been completed. It concerned the application of quantum theory to the modeling of human similarity judgments. Thus, this grant and the AFOSR one complemented each other, since the Leverhulme grant concerned the application of quantum theory to similarity and the AFOSR one to decision making. Note, the Leverhulme is a prestigious funding organization in the UK and is known for favoring research projects of particularly high transformative potential.

-Other University Collaborations

My current collaborators include:

Irina Basieva, Linnaeus University
Jerome Busemeyer, Indiana University
James Hampton, City University London
Stephen Lea, Exeter University
Richard Shiffrin, Indiana University
Katy Tapper, City University London
Jennifer Trueblood, Vanderbilt University
Stephen Veheyen, Leuven University
Wouter Voorspoels, Leuven University
Lee White, independent organizational consultant
Thom Wilcockson, Lancaster University
Andy Wills, Plymouth University
James Yearsley, Vanderbilt University

-Other projects with Military or Government involvement

None.